Summary of the EHE Online Alert

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Abstract

A new online IceCube analysis is being proposed targeting high energy neutrino induced tracks with energies exceeding several hundreds TeV. The expected contribution from an Astrophysical signal with γ = -2 and Φ = 1e-18 $\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ is 4 events per year with a background rate of 2 events per year. These tracks are excellent follow-up candidates as they have a median angular resolution of 0.22° and benefit from a high signal purity.

1 Motivation

IceCube has unambiguously observed astrophysical neutrinos with a variety of analyses [2, 3], however their doesn't seem to be a common hot spot for the observed events. This could indicate the sources of our highest energy events are transients or flaring, which naturally suggests that IceCube should make these events available to every observatory willing to follow them up as quickly as possible.

The analysis described in the following sections represents one way to extract a very pure, high energy track sample averaging 4-6 events per year with 2-4 of those events being of astrophysical origin. These tracks have a median angular resolution of 0.22° that is nearly flat across the energy spectrum. With this remarkable pointing and high purity sample, prompt followup of these events will play a key role in uncovering the source of astrophysical neutrinos.

2 EHE Online Alert

The selection for the online EHE alert is a modification of the diffuse Extremely High Energy (EHE) neutrino search [1] that yielded the first observed PeV neutrino events. Modifications to the analysis selection were made to increase the purity in tracks and to increase the sensitivity for PeV neutrinos. This was accomplished by tightening the requirement on the fit quality and re-optimizing the two-dimensional cut in the plane of $\cos(\theta)$ and $\log_{10}(\mathrm{NPE})$. The full selection is described below.

2.1 Selection

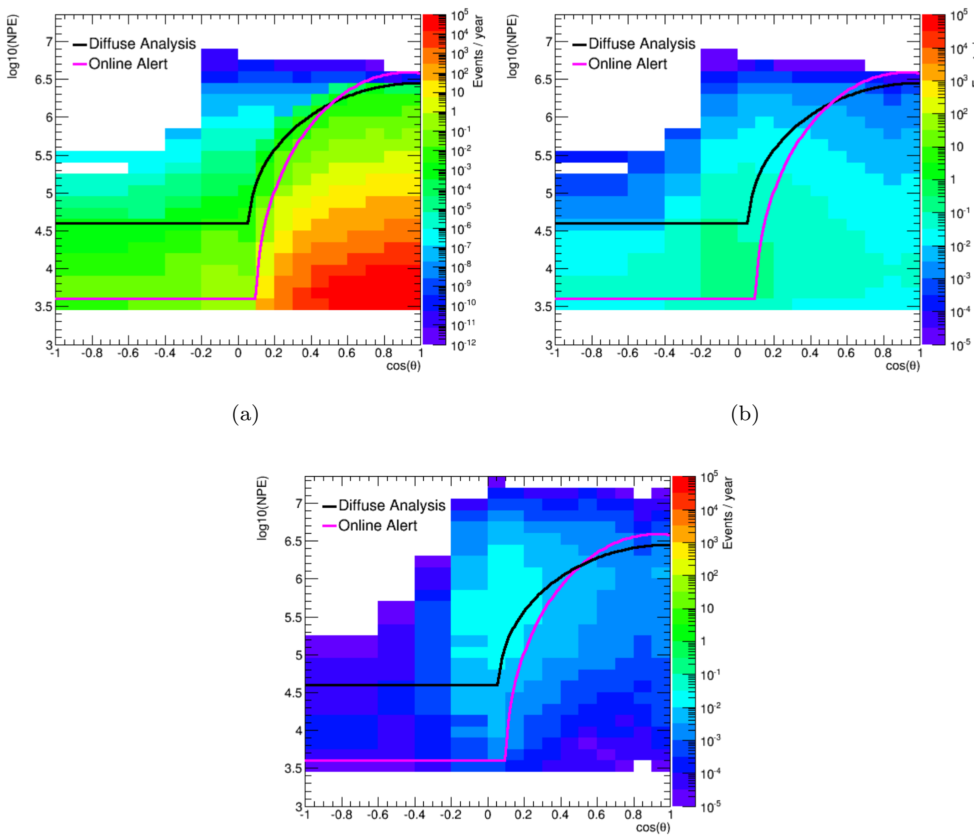
The EHE alert is build on top of a preselection at the pole to filter out high energy events by requiring at least $10^{3.6}$ NPE. This reduces the data rate to 26 mHz before running more computationally intensive reconstructions.

The online alert places a requirement on the fit quality parameter calculated using a charge weighted χ^2. The requirement is placed on the $\chi^2/ndof < 80$, which is more strict than the offline diffuse EHE analysis in order to preferentially select track-like events.

The final requirement is a two dimensional cut placed in $\log_{10}$(NPE) and $\cos(\theta)$. This cut criteria was optimized using simulated events weighted to an astrophysical E^{-2} spectrum. The most optimal selection found was to keep events satisfying the following criteria:

- if $\cos(\theta) < 0.1$, then $\log_{10}(\text{NPE}) > 3.6$
- if $\cos(\theta) > 0.1$, then $\log_{10}(\text{NPE}) > 3.6 + 2.99\times\sqrt{1 - (\frac{cos(\theta)-0.93}{0.83})^2}$

This 2D requirement, along with the diffuse analysis selection, is illustrated in Figure 1, and the increase in sensitivity by changing the 2D requirement can be seen in Figure 2.



(a) (b)

(c)

Figure 1: The two-dimensional plane of $\cos(\theta)$ and $\log_{10}$(NPE) for (a) the summed background (Atmos. μ and ν_μ), (b) signal (Astro. ν_μ), and (c) the expected GZK signal. These are weighted using 1 year of livetime.

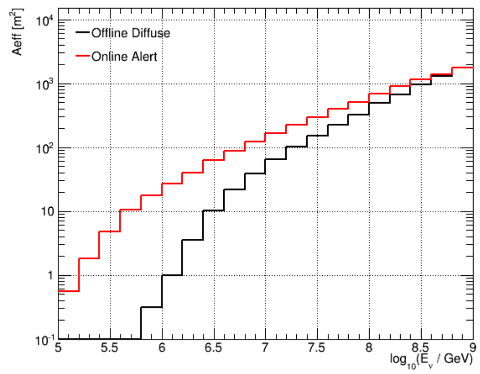


Figure 2: The effective area for the diffuse EHE two-dimensional selection and the EHE Alert two-dimensional selection.

2.2 Expected and Observed Event Rate

The expected event rate for signal is estimated from simulated ν_μ events weighted to an E^{-2} spectrum with astrophysical normalization at 1.08×10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1}. The atmospheric μ and ν_μ backgrounds are also estimated from simulation. The total yields are given in Table 1.

Sample	Yield / year
Atmos. μ	0.52
Conv. Atmos. ν_μ	1.20
Prompt Atmos. ν_μ	0.19
Total Background	1.91
Astro. ν_μ	4.09

Table 1: A table summarizing the expected event yield for the EHE online alert for each sample for an assumed livetime of 1 year.

In addition to this prediction, the event rate has been validated using four years of IceCube data. The observed rate is in agreement with background + signal hypothesis if the global fit results [4] are assumed, which puts the spectral normalization at 2.3 x 10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1} and spectral index at -2.49. In this case the expected astrophysical ν_μ signal is 2.48 events per year. The observed data counts are given below in Table 2. Each event has been viewed in an event display to confirm that they are, in fact, tracks.

Year	2012	2013	2014	2015
Yield	4	4	5	4

Table 2: Summary table of the number of events passing the EHE Alert Selection in the four years of data analyzed.

One particularly useful piece of information for observatories is where the majority of these events will fall in declination. It will aid them in deciding whether or not to subscribe to the EHE Alert stream that this paper is proposing. To that end, the event rate vs declination is shown in Figure 3.

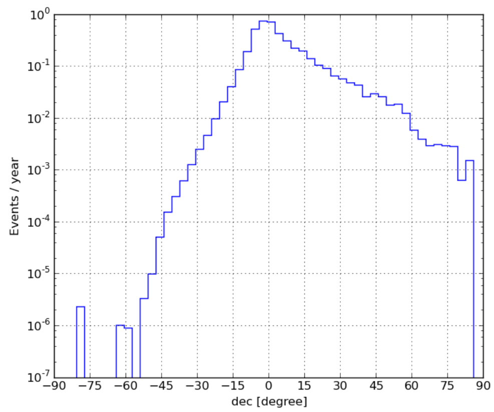


Figure 3: The expected event rate for a given declination as estimated from simulated muon neutrino events following an E^{-2} spectrum with astrophysical normalization of 1.08×10^{-18} $\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$

2.3 Angular Resolution

The angular resolution has been studied utilizing simulated ν_μ events satisfying the selection detailed in Section 2.1 by investigating the opening angle between the best available online fit to the observed muon track and the true neutrino direction. The median angular resolution is found to be $0.22°$ and is nearly flat across the neutrino energy spectrum, as illustrated in Figure 4.

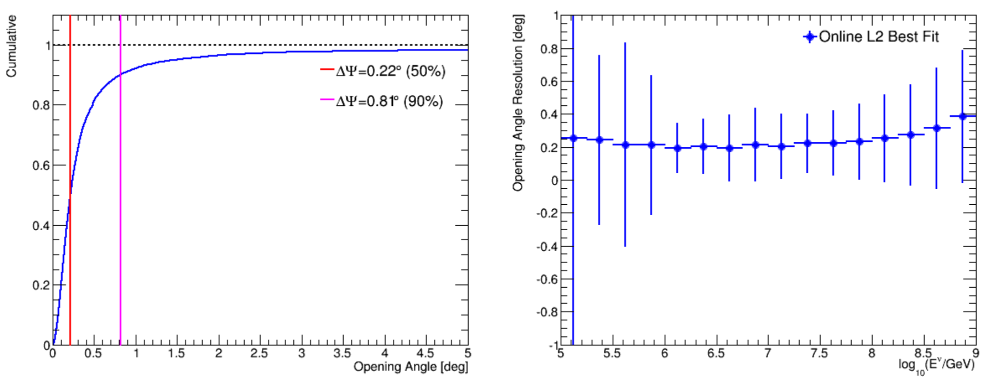


Figure 4: On the left is the cumulative distribution for the opening angle with lines showing the points where 50% and 90% of all simulated events are behind. On the right is the median angular resolution binned in neutrino energy. The errors shown are statistical only.

2.4 Information Sent

The information that we will share with other observatories in the alert is summarized in the Table 3.

Parameter	Description	Format / Unit	Comments
TITLE	"GCN/AMON Notice"		
NOTICE_DATE	"GCN Notice Time"	UT	
SRC_RA	Right Ascension of the event	[deg]	
SRC_DEC	Declination of the event	[deg]	
SRC_ERROR	Angular uncertainty of the event	[deg]	
DISCOVERY_DATE	Event arrival time	TJD and DOY and (yy/mm/dd)	
DISCOVERY_TIME	Event arrival time	SOD and UT	
SIGNALNESS	The probability of the event being an astrophysical neutrino as estimated from simulation.	N/A	Values range from 0 to 0.95. If an event in data falls outside of the simulation coverage, the signalness value is set to -1. See the description below and Figure 5.
SAME_AS_HESE	This parameter describes whether a given alert is due to the same neutrino event (same run number and same event number) as a previous alert from another (HESE) stream or unique.	N/A	0 if alert is unique, 1 if it is dual with an alert from HESE stream. Most of the time alert will be unique (i.e. value of 0).
REVISION	Revision number of this EHE alert		The default value will be 0. See Section 2.5 for more information.
SRC_ID_NUM	Unique ID Number		
STREAM	Stream Number (AMON)		AMON stream number (=2 for EHE)
COMMENTS	"AMON_ICECUBE_EHE"		
SUN_POSTN	(RA, Dec) of the sun	[deg] and ([h,m,s],[d,,])	
SUN_DIST	Angular distance of the event relative to the Sun	[deg]	Also Sun_angle in [hr] (East of Sun)
MOON_POSTN	(RA, Dec) of the moon	[deg] and ([h,m,s],[d,,])	
MOON_DIST	Angular distance of the event relative to the Moon	[deg]	
N_EVENTS	The number of neutrino events in the alert		n = 1
DELTA_T	Time Window		N/A – Fixed at 0
SIGMA_T	Error on the time window		N/A – Fixed at 0

Table 3: The table summarizing what information will be included in the alert. TJD = Truncated Julian Date, DOY = Days of Year, SOD = Seconds of Day in units of centi-seconds (seconds multiplied by 100 and then integerized).

The signal-ness parameter is estimated from simulation by creating a two-dimensional probability map in the plane of $\cos(\theta)$ and $\log_{10}$(NPE), following:

$$P_{i,j} = N_{i,j}^{sig}/(N_{i,j}^{sig} + N_{i,j}^{bkg}), \qquad (1)$$

where i and j are the bins in the 2D plane, N^{sig} is the expected Astrophysical ν_μ signal (assuming an E^{-2} spectrum) in the ij-th bin, and N^{bkg} is the expected Atmospheric μ and ν_μ background in the ij-th bin. The resulting map can be seen in Figure 5. Bins are only filled if there are a minimum expectation from simulation of 10^{-4} events / year. The probability is capped at 95% due to limited statistics in simulation. In the event that a data event falls within the white space where we do not have Monte Carlo coverage, the signal-ness value is set to -1.

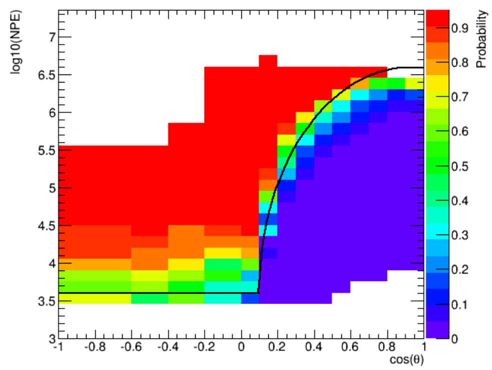


Figure 5: The two-dimensional signal-ness map in the plane of $\cos(\theta)$ and $\log_{10}(\text{NPE})$ derived from simulated events. Bins are only filled if a minimum threshold of signal events are met, and empty bins are indicated by white space.

2.5 Potential Revision

Each alert that is sent will have a default revision value of 0, as listed in Table 3. After the arrival of the full event data in the north, a shift monitor will have the option to retract the alert if the event does not appear to be a track. At this time, there isn't a plan in place to run additional reconstructions in the north, however this may be worth exploring in the future. For now, given the robust selection and strong performance of the online angular reconstruction, it is the hope to get these alerts online as soon as possible.

References

[1] The IceCube Collaboration. First Observation of PeV-Energy Neutrinos with IceCube. *Phys. Rev. Lett.*, 111:021103, Jul 2013.

[2] The IceCube Collaboration. Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data. *Phys. Rev. Lett.*, 113:101101, Sep 2014.

[3] The IceCube Collaboration. Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube. *Phys. Rev. Lett.*, 115:081102, Aug 2015.

[4] The IceCube Collaboration. Measurement of the Diffuse Neutrino Flux by a Global Fit to Multiple IceCube Results. *Phys. Procedia*, 61:435–442, 2015.